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2012 ESTCP Live Site Demonstrations Massachusetts Military Reservation Camp Edwards, MA

ESTCP MR-1165

Demonstration Data Report Central Impact Area TEMTADS MP 2×2 Cart Survey

James B. Kingdon
Dean A. Keiswetter
Thomas H. Bell

SAIC, Inc.
Arlington, Virginia

Matthew Barner
Andrew Louder
Andrew Gascho
Tamir Klaff

CH2M HILL
Chantilly, Virginia

Glenn R. Harbaugh
Daniel A. Steinhurst

Nova Research, Inc.
Alexandria, Virginia

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6. AUTHOR(S)
James B. Kingdon,[1] Dean A. Keiswetter,[1] Thomas H. Bell,[1] Matthew Barner,[2] Andrew Louder,[2] Andrew Gascho,[2] Tamir Klaff,[2] Glenn R. Harbaugh,[3] and Daniel A. Steinhurst[3]

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[1]SAIC, Inc. - ASAD, 4001 N. Fairfax Drive, 4th Floor, Arlington, VA 22203
[2]CH2M HILL, 15010 Conference Center Drive, Suite 200, Chantilly, VA 20151
[3]Nova Research, Inc., 1900 Elkin Street, Suite 230, Alexandria, VA 22308

14. ABSTRACT
The TEMTADS MP 2×2 Cart was demonstrated at the Central Impact Area of the Massachusetts Military Reservation, MA, during June 2012 as part of the ESTCP Live Site Demonstrations. The TEMTADS MP 2×2 Cart is designed to be deployable in areas inaccessible to vehicle-towed arrays. TEM data are collected at each target location while the cart is stopped, with an on-target collection time of approximately 1 minute. The data are inverted to determine the principal axis eddy current decay functions of the targets. Classification is based on comparing the eddy current decay functions for each target with those of the various munitions targets of interest at the site, as well as a variety of clutter items that are representative of the non-hazardous metal debris at the site. We report the classification performance results with the cart for approximately 1,300 unknown targets at the Central Impact Area of the Massachusetts Military Reservation, MA.

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Acronyms

Abbreviation	Definition
AOL	Advanced Ordnance Locator
APG	Aberdeen Proving Ground
ASCII	American Standard Code for Information Interchange
CIA	Central Impact Area
EMI	Electro-Magnetic Induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
IVS	Instrument Verification Strip
MMR	Massachusetts Military Reservation
MP	Man-Portable
MR	Munitions Response
MTADS	Multi-sensor Towed Array Detection System
NRL	Naval Research Laboratory
POC	Point of Contact
QC	Quality Control
RMS	Root-Mean-Squared
Rx	Receiver
SAIC	Science Applications International Corporation
TEM	Time-domain Electro-Magnetic
TEMTADS	Time-domain Electro-Magnetic MTADS
TOI	Target of Interest
Tx	Transmit(ter)
UXO	Unexploded Ordnance

1.0 INTRODUCTION

1.1 ORGANIZATION OF THIS DOCUMENT

The results of the Naval Research Laboratory (NRL) Man-Portable Electromagnetic Induction Array for UXO Detection and Discrimination, or TEMTADS Man-Portable (MP) 2x2 Cart, demonstration at the Central Impact Area (CIA), Massachusetts Military Reservation (MMR), located at Camp Edwards, MA in June 2012 are presented in this document. This demonstration was part of the 2012 Environmental Security Technology Certification Program (ESTCP) Munitions Response Live Site Demonstrations. To limit the repetition of information, Study- and site- specific information that are presented elsewhere, such as in the ESTCP Live Site Demonstrations Plan [1], are noted and not repeated in this document.

1.2 STUDY BACKGROUND AND OBJECTIVES

Please refer to the ESTCP Live Site Demonstrations Plan [1].

1.3 SPECIFIC OBJECTIVES OF DEMONSTRATION

As part of NRL's ESTCP-funded Live Site Demonstrations, NRL conducted a cued classification survey within the 3-acre man-portable subarea selected from part of the 330-acre CIA. Cued data collection was conducted for 1,001 anomalies identified from an EM61-MK2 cart survey recently conducted by a National Guard Bureau contractor. The NRL TEMTADS MP 2x2 Cart (MP System) was used for this survey. Data collection was conducted for an additional 300 anomalies from the 3-acre MetalMapper subarea for inter-system performance comparison. Characterization of system response to the Targets of Interest (TOIs) was based on previously acquired TEMTADS reference data augmented with onsite measurements. These data were collected in accordance with the overall study objectives and demonstration plan.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

2.1.1 TEMTADS/3D EMI Sensors

The original design of the MP System utilized the standard TEMTADS Electromagnetic Induction (EMI) sensor. Based on the results of the MP system demonstration at the Aberdeen Proving Ground (APG) Standardized UXO Test Site in August, 2010 [2,3], revision of the sensor technology was indicated. A modified version of the sensor element was designed and built, replacing the single, vertical-axis receiver coil of the original sensor with a three-axis receiver cube. These receiver cubes are similar in design to those used in the second-generation Advanced Ordnance Locator (AOL) and the Geometrics MetalMapper (ESTCP MR-200603) system with dimensions of 8 cm rather than 10 cm. The CRREL MPV2 system (ESTCP

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MR-201005) uses an array of five identical receiver cubes and a circular transmitter coil. The new sensor elements are designed to have the same form factor as the original, aiding in system integration. A TEMTADS/3D coil under construction is shown in Figure 2-1.

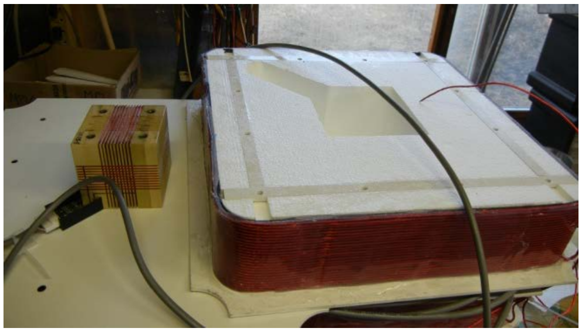

Figure 2-1 – Individual TEMTADS/3D EMI sensor with 3-axis receiver under construction.

Minor modifications were made to the AOL control and data acquisition infrastructure to make it compatible with our deployment schemes. Decay data are collected with a 500 kHz sample rate until 25ms after turn off of the excitation pulse. This results in a raw decay of 12,500 points; too many to be used practically. These raw decay measurements are grouped into 122 logarithmically-spaced "gates" with center times ranging from 25 μs to 24.35 ms with 5% widths and are saved to disk.

2.1.2 Application of the Technology

Application of this technology was straightforward. A list of target positions was developed from some source. In the case of this demonstration, the anomaly list was derived from EM61-MK2 data recently collected by the National Guard Bureau contractor. The ESTCP Program Office combined the anomaly list with the locations of the emplaced seed munitions items and generated the final target list. A plastic pin flag was manually placed over each anomaly location prior to cued data collection. The cart was positioned over each target in turn and the transmitter for each array sensor was fired in sequence. Decay data were collected from all twelve receive coils for each excitation. These data were then stored electronically on the data acquisition computer. Prior to moving to the next target, the operator evaluated a display of the 4 monostatic, 3-axis signal amplitude decays and compared the values at the first usable time gate (89 μs) to a 'low SNR' threshold (nominally 5 mV/Amp). If no amplitude was above the threshold, the operator had the option to collect additional data for the target prior to leaving the target location.

In the next version of this technology, the facility for conducting a 'quick and dirty' inversion prior to the operator moving the array will be implemented. For this demonstration, the inversions were performed off-line so that we had the ability to intervene in the data processing pipeline as required. The EMI data were transferred to the analyst several times each day for near real-time analysis at the demonstration site.

2.1.3 Development of the Technology

The MP System is a man-portable four-element transient EMI (TEM) system designed and built by NRL with funding from ESTCP to transition the TEM sensor technology of the TEMTADS towed array (ESTCP Project MR-200601) to a more compact, man-portable configuration for use in more limiting terrain under project MR-200909. This system was initially configured to operate in a cued mode, where the target location is already known. Preliminary testing of the initial system configuration [4] found that for high SNR (≥ 30) targets one measurement cycle provided enough information to support classification. For deeper and/or weaker targets, more robust estimates of target parameters were obtained by combining two closely-spaced measurements. Two measurements per anomaly were typically made proactively to avoid the potential need to revisit a target a second time. As part of project MR-200909, a demonstration was conducted to rigorously investigate the capabilities of this new sensor platform for unexploded ordnance (UXO) classification in a cued data collection mode at the APG Standardized UXO Test Site in August, 2010 [5]. Those results indicated that the inversion performance of the system was not comparable to that of the full TEMTADS array for lower SNR targets due to the limits of the smaller data set (fewer looks at the target). Revision of the sensor technology was indicated for the MP System to collect sufficient data over an anomaly. A modified version of the EMI sensor was designed and built, replacing the single, vertical-axis receiver loop of the original coil with a tri-axial receiver cube. These receiver cubes are identical in design to those used in the CRREL MPV2 system (ESTCP MR-201005). The new sensor elements were designed to have the same form factor as the originals, aiding in system fabrication. The completed MP system was demonstrated as part of the ESTCP Munitions Response Live Site Demonstrations at the former Camp Beale, CA in June, 2011 [6] and at the former Spencer Artillery Range, TN in May, 2012 [7].

As part of the former Spencer Artillery Range demonstration, the MP System was deployed in a dynamic mode to collect survey data for a small portion of the site prior to cued data collection. The results were encouraging [7] and the analysis of the data is ongoing.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The TEMTADS 5x5 Array was designed to combine the data advantages of a gridded survey with the coverage efficiencies of a vehicular system. The resultant data should therefore be equal, if not better, in quality to the best gridded surveys (the relative position and orientation of the sensors will be better than gridded data) while prosecuting many more targets each field day.

There are obvious limitations to the use of this technology. The TEMTADS 5x5 Array is 2-m square in area and mounted on a trailer. Fields where the vegetation or topography interferes with passage of a trailer of that size will not be amenable to the use of the present array.

The MP system was designed to offer similar production rates in difficult terrain and treed areas that the TEMTADS 5x5 Array cannot access. With the upgraded TEMTADS/3D sensors, similar performance can be achieved with similar classification-grade data quality. The MP array is 80

cm on a side and mounted on a man-portable cart. Terrain where the vegetation or topography interferes with passage of a cart of that size will not be amenable to the use of the system.

The other serious limitation is anomaly density. For all systems, there is a limiting anomaly density above which the response of individual targets cannot be separated individually. We have chosen relatively small sensors for this array which should help with this problem but we cannot eliminate it completely. Recent developments, including solvers designed for classification in multiple-object scenarios such as SAIC's multi-target solver [8], are being evaluated and their performance characteristics in cluttered environments determined.

3.0 PERFORMANCE OBJECTIVES

Specific performance objectives for the demonstration were established to provide a basis for evaluating the performance and costs of the demonstrated technology. They are given in Table 3-1. These objectives are for the technology being demonstrated only. Overall project objectives were given in the overall demonstration plan generated by ESTCP. Since this is a classification technology, the performance objectives focus on the second step of the UXO survey problem; we assume that the anomalies from all targets of interest have been detected and included on the target list we worked from.

Table 3-1 – Performance Objectives for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Instrument Verification Strip (IVS) Results	System responds consistently to emplaced items	Daily IVS data	≤ 10% RMS variation in β amplitudes and fit depth
Cued Interrogation of Anomalies	Instrument position	Cued data	The center of the instrument was positioned within 40 cm of actual target location for 100% of the anomalies

3.1 OBJECTIVE: INSTRUMENT VERIFICATION STRIP (IVS) RESULTS

This objective demonstrates that the sensor system was in good working order and collecting physically valid data each day. The Instrument Verification Strip was surveyed twice daily. The amplitude of the derived response coefficients and the fit depth for each emplaced item were compared to the running average of the demonstration for reproducibility.

3.1.1 Metric

The reproducibility of the measured response of the sensor system to the emplaced items defined this metric.

3.1.2 Data Requirements

The tabulated fit parameters for the data corresponding to each emplaced item in terms of derived response coefficients and depth.

3.1.3 Success Criteria

The objective was considered met if the RMS amplitude variation of the derived response coefficients and for the fit depth was less than 10%.

3.2 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

To collect EMI data of the highest quality for UXO/clutter classification, the anomaly must be illuminated along its three principle axes. To ensure this, the data collection pattern (in this case the TEMTADS array) must be positioned directly over the center of the anomaly.

3.2.1 Metric

The metric for this objective was the percentage of anomalies where the center of the instrument during data collection was within the acceptable distance of the actual target location.

3.2.2 Data Requirements

As the MP System does not have integrated positioning, performance was determined by the offset of each inverted target location from the center of the sensor system. After any reacquisition cycles directed by the data QC process, the offset distance was required to be less than 40cm.

3.2.3 Success Criteria

The objective was considered met if the center of the instrument was positioned within 40 cm of the anomaly fit location for 100% of the cued anomalies. Exceptions were allowed for anomalies where the indicated fit location was within the perimeter of an obstacle such as a tree.

4.0 SITE DESCRIPTION

Please refer to the ESTCP Live Site Demonstrations Plan [1].

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The demonstration was executed in two stages. The first stage involved characterization of the MP System with respect to the site-specific TOIs and to the site-specific geology. The background response of the demonstration site, as measured by the MP System, was characterized throughout the demonstration as part of the data collection process. A test pit was provided onsite, near the IVS, and several site-specific TOIs were provided. Those TOI which did not already have a set of magnetic polarizability decays in our library were measured as outlined in the Program Office Demonstration Plan. These data were provided to the Program Office for use as training data for the data processing demonstrators.

The second stage of the demonstration was the cued survey of a portion of the Man-Portable subarea of the demonstration site using the MP System. The first 1,001 anomalies, which were located in the northern 1.2 acres of the subarea were surveyed. For each anomaly, a plastic pin flag was placed on the reported position using RTK GPS. The array was then positioned roughly over the center of each flagged anomaly and a data set collected. At the request of the Program Office, 300 anomalies were also measured on the eastern edge of the MetalMapper subarea. Each data set was then inverted using the data analysis methodology discussed in Section 6.0, and estimated target parameters determined. The results and the archive data were then submitted to the Program Office.

The schedule of field testing activities is provided in Figure 5-1 as a Gantt chart.

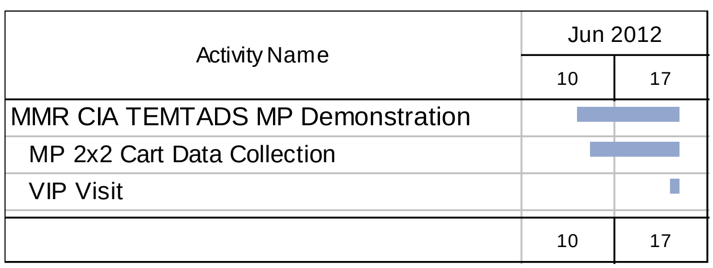

Figure 5-1 – Planning Schedule of Field Testing Activities

5.2 SITE PREPARATION

Please refer to the ESTCP Live Site Demonstrations Plan [1].

5.3 SYSTEMS SPECIFICATION

This demonstration was conducted using the NRL TEMTADS MP 2x2 Cart.

5.3.1 TEMTADS MP 2x2 Cart

The MP System is a man-portable system comprised of four of the TEMTADS/3D EMI sensors discussed in Section 2.1.1 arranged in a 2x2 array as shown schematically in Figure 5-2. The MP System, shown in Figure 5-3 (left) at APG, is fabricated from PVC plastic and fiberglass. The center-to-center distance is 40 cm yielding an 80 cm x 80 cm array. The array is typically deployed on a set of wheels resulting in a sensor-to-ground offset of approximately 18 cm. The transmitter electronics and the data acquisition computer are mounted in the operator backpack, as shown in Figure 5-4. The MP System can be operated in two modes; dynamic or survey mode and cued mode. In dynamic mode, a Global Positioning System (GPS) antenna and (optionally) an inertial measurement unit (IMU) are mounted above the TEM array as shown in Figure 5-3 (right). Data collection is controlled in dynamic mode using G&G Science's EM3D application suite, similar to that used for the Geometrics MetalMapper systems. In cued mode, the locations of the anomalies must already be known and flagged for reacquisition. Custom software written by NRL provides cued data acquisition functionality. In the future, the system will be configured to record location from the GPS and orientation from the IMU, if available. The controller unit provided by the GPS vendor can be loaded with a list of virtual flags and used for anomaly-to-anomaly navigation.

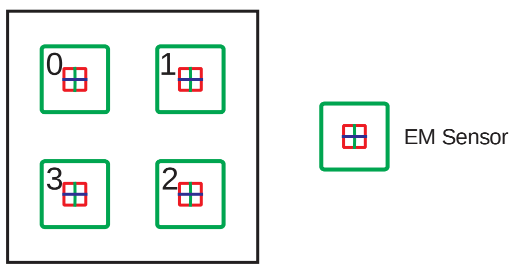

Figure 5-2 – Sketch of the EMI sensor array showing the position of the four sensors. The tri-axial, revised EMI sensors are shown schematically.

Figure 5-3 – The NRL TEMTADS Man-Portable 2x2 Cart (left) and TEMTADS MP 2x2 Cart with GPS Antenna Tripod (right)

Figure 5-4 – TEMTADS 2x2 Electronics Backpack

5.3.2 Data Acquisition User Interface

The data acquisition computer is mounted on a backpack worn by one of data acquisition operators. The second operator controls the data collection using a tablet computer which wirelessly (IEEE 802.11g) communicates with the data acquisition computer. The second operator also manages field notes and team orienteering functions. In Figure 5-5 (left), a data collection team is shown with a safety escort. The tablet PC user interface is shown in Figure 5-5 (right).

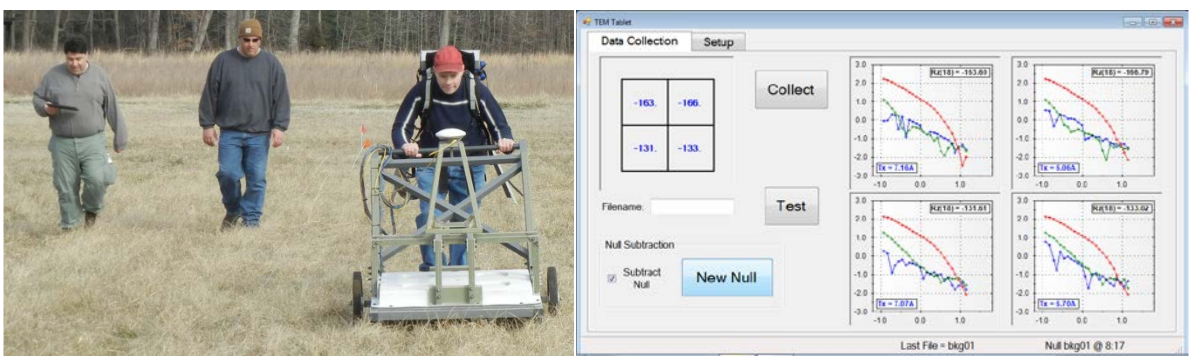

Figure 5-5 – TEMTADS 2x2 MP Cart and Data Acquisition Operators (left) and Screenshot of Tablet Computer Interface (right)

5.4 CALIBRATION ACTIVITIES

5.4.1 TEMTADS Sensor Calibration

For the TEMTADS family of platforms, a significant amount of data has been collected with the systems as configured at our Blossom Point facility, both on test stands, on our test field [9] and during our demonstrations at APG [10], the former Camp San Luis Obispo [11], the former

Camp Butner [12], the former Camp Beale [6], the former Mare Island Naval Shipyard [13], and the former Spencer Artillery Range [7]. These data and the corresponding fit parameters provide us with a set of reference parameters including those of clear background (i.e. no anomaly present).

Daily calibration efforts consisted of collecting background (no anomaly) data sets periodically throughout the day at quiet spots to determine the system background level for subtraction. An initial set of background spots were selected from the EM61-MK2 data and vetted with the MP System prior to continued use. Only a small number of preselected background spots were found to be viable. An all-metal metal detector was then used to find additional backgrounds spots, as shown in Figure 5-6. For the MetalMapper subarea, no background spots could be found, so the array was lifted in the air to chest height at frequent intervals by team members with all metal removed from their persons. The items emplaced in the IVS were measured twice daily to monitor the variation in the system response. These two types of measurements constituted the daily calibration activities. Test pit measurements were made to determine the responses for site-specific TOI that were not already available in our reference library of TOI fit parameters.

Figure 5-6 – Team Member Searching for Background Spots using Hand-Held All-Metal Detector

5.4.2 Background Variation Data

A group of anomaly-free areas along the road bisecting the ManPortable subarea were identified in advance from the EM61-MK2 data set and by inspection with a hand-held all-metal metal detector. An example of a background measurement being made is shown in Figure 5-7. Each background location was confirmed to be anomaly-free prior to prolonged use with the MP System. Any location found to exhibit an anomaly was discarded and not used further. Since the viable locations all provided roughly comparable responses, a convenient subset of the locations was chosen to be visited periodically throughout each day of the demonstration. All 71 background measurements taken for the duration of the survey are shown in Figure 5-8, and are presented as the mean and standard deviation of the four monostatic measured signals. Dates are presented as Julian dates, or the day of the year. June 15, 2012 is Julian date 167. Table 5-1

tabulates the intraday variations of the mean and standard deviation quantities from Figure 5-8. The y-axis value for background #10 on June 16, 2012 was anomalously high. The transmit waveform for Transmitter Tx3 was non-nominal for this background measurement. Therefore the background was not used for data processing.

Figure 5-7 – Team Members Preparing for a Background Measurement

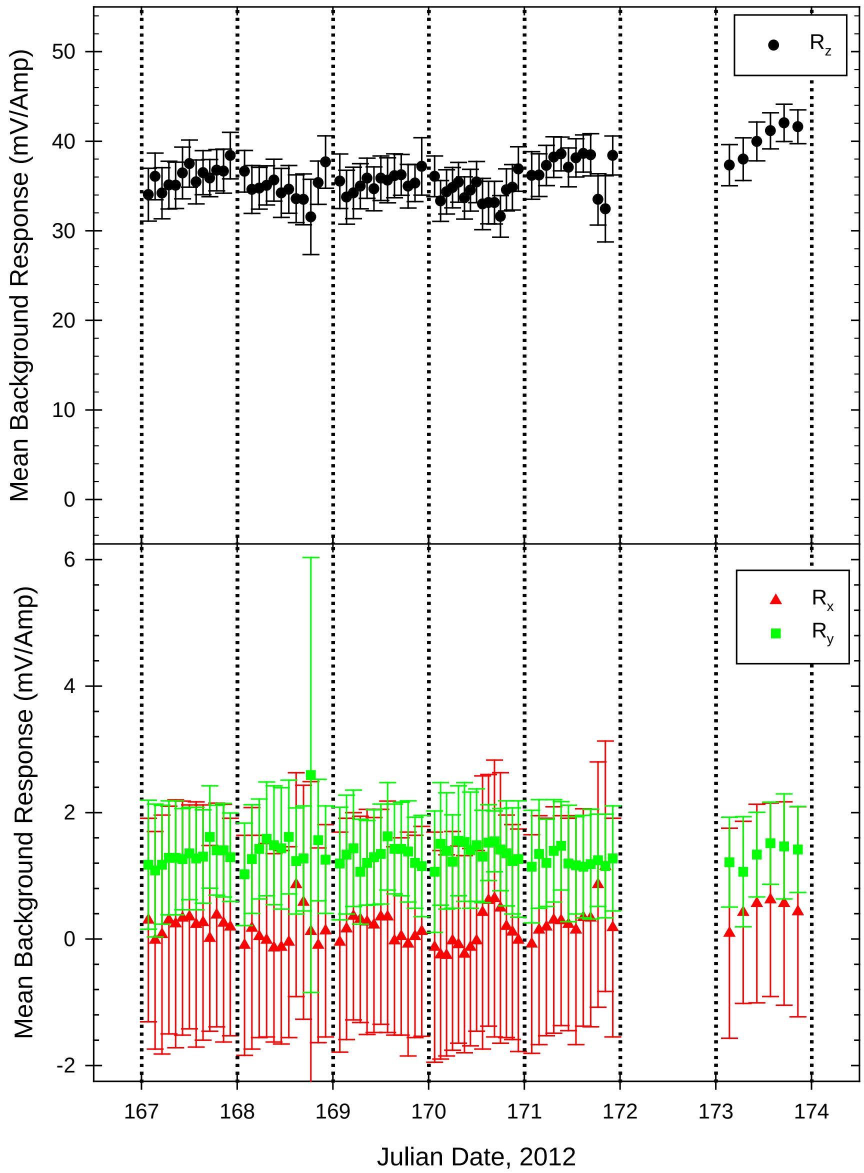

Figure 5-8 – Intra- and inter- daily variations in the response of the MP System to background anomaly-free areas through the duration of the demonstration. The upper panel plots the average measured signal of the four monostatic, Z-axis quantities at 0.089 ms, while the bars represent the standard deviation of those quantities (i.e. 1σ about the mean). The red and green points in the lower panel plot the average measured signal of the four monostatic, X- and Y-axis quantities at 0.089 ms, respectively.

Table 5-1 – Summary of the Daily Variation in the Mean and Standard Deviation of the Signals Measured for the MP System Background Areas.

Date	# of Bkgs.	Mean Z (mV/Amp)	Std. Dev. Z (mV/Amp)	Mean Y (mV/Amp)	Std. Dev. Y (mV/Amp)	Mean X (mV/Amp)	Std. Dev. X (mV/A)
6/15/2012	13	36.00	2.55	1.30	0.82	0.22	1.78
6/16/2012	12	34.76	2.46	1.47	1.07	0.11	1.64
6/17/2012	13	35.41	2.54	1.31	0.78	0.16	1.68
6/18/2012	15	34.31	2.28	1.38	0.79	0.09	1.73
6/19/2012	12	36.92	2.33	1.24	0.79	0.34	1.72
6/21/2012	6	40.01	2.14	1.33	0.73	0.45	1.58

5.4.3 Instrument Verification Strip Data

The IVS was provided onsite to verify the repeatability of the response of the MP System to several examples of TOI. Details of the contents of the CIA IVS are given in Table 5-2. Each emplaced item in the IVS was measured twice daily, once before starting the data collection process and a second time before shutting the system down at the end of each day. The shotput was not emplaced until the penultimate survey day.

Table 5-2 – Details of Central Impact Area IVS

ID	Description	Easting[a] (m)	Northing[a] (m)	Depth (m)	Inclination	Orientation
T-001	Shotput	372,245.059	4,618,639.045	0.25	N/A	N/A
T-002	155mm Projectile	372,247.659	4,618,635.945	0.50	Horizontal	Across Track
T-003	81mm Mortar	372,250.272	4,618,632.972	0.30	Horizontal	Across Track
T-004	Blank	372,252.872	4,618,629.872	N/A	N/A	N/A
T-005	Medium ISO	372,255.575	4,618,626.492	0.30	Horizontal	Across Track

[a] Positions T-001 and T-004 were initially open holes and not precisely located prior to or during the demonstration. Reported positions are estimated.

All data sets for each of the emplaced IVS items were inverted using the data analysis methodology discussed in Section 6.0, and the estimated target parameters determined. As geolocation is not currently provided to the MP System in cued mode, only the variability in the inverted depth of each target was monitored for the MP System.

The results for the ten cued mode IVS measurements are given in Table 5-3 and shown in Figure 5-9. As the shotput was only available for the last two days of the survey, the aggregate values for the shot only represent four measurements. The RMS variation in the magnetic polarizability amplitudes at 0.089 ms were less than 3% of the mean amplitude for all IVS items and for all three magnetic polarizabilities. The aggregate depth error statistics for the IVS items are listed in Table 5-4 and shown in Figure 5-10. Depth error is expressed as the difference between the fitted depth and the listed emplacement depth. The RMS variation in the depth errors for each emplaced IVS item was 3 cm (2%) or less.

Table 5-3 –Summary of the Amplitude Variations at 0.089 ms in the Derived Response Coefficients for All Items Emplaced in the IVS.

Item	β_1 Amplitude (m^3)				β_2 Amplitude (m^3)				β_3 Amplitude (m^3)			
	Min	Max	Mean	RMS	Min	Max	Mean	RMS	Min	Max	Mean	RMS
Shotput	2.21	2.25	2.233	0.02	2.19	2.24	2.21	0.02	2.10	2.14	2.12	0.02
155mmP	17.16	19.01	18.32	0.53	15.90	16.89	16.42	0.32	13.51	14.03	13.80	0.13
81mmM	4.46	4.89	4.668	0.12	1.33	1.40	1.36	0.03	1.24	1.30	1.27	0.02
Med. ISO	1.69	1.77	1.73	0.031	0.94	1.01	0.98	0.02	0.92	0.96	0.94	0.01

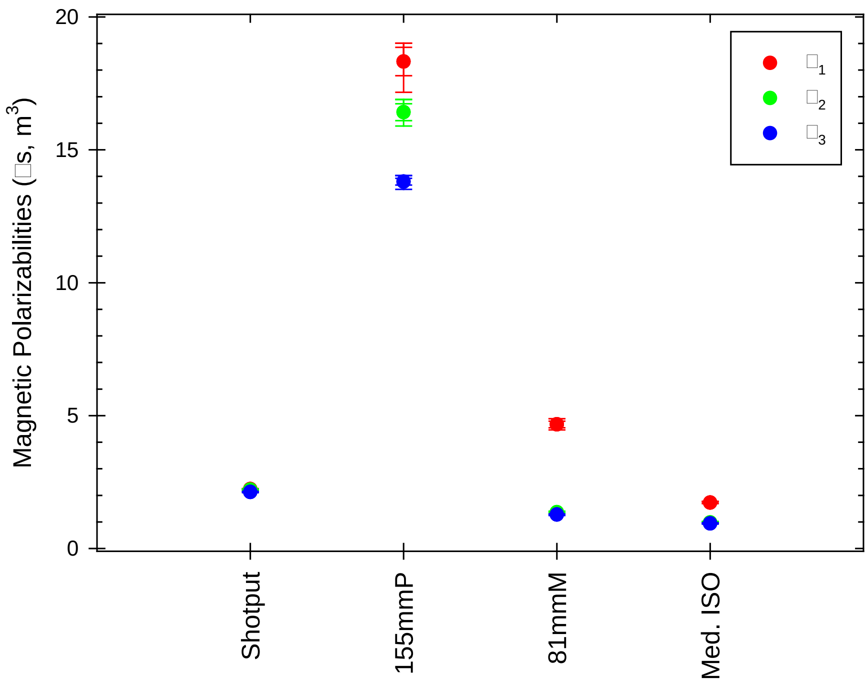

Figure 5-9 – Amplitude variations at 0.089 ms in the derived response coefficients for all items emplaced in the IVS. β_1 is in red; β_2 is in green; and β_3 is in blue.

Table 5-4 –Summary of Depth Error Statistics for all items emplaced in the IVS.

Item	Depth Error (cm)			
	Min	Max	Mean	RMS
Shotput	0.30	1.40	1.00	0.5
155mmP	-2.70	-0.90	-1.80	0.5
81mmM	-3.50	-2.00	-3.00	0.4
Med. ISO	0.80	2.10	1.50	0.4

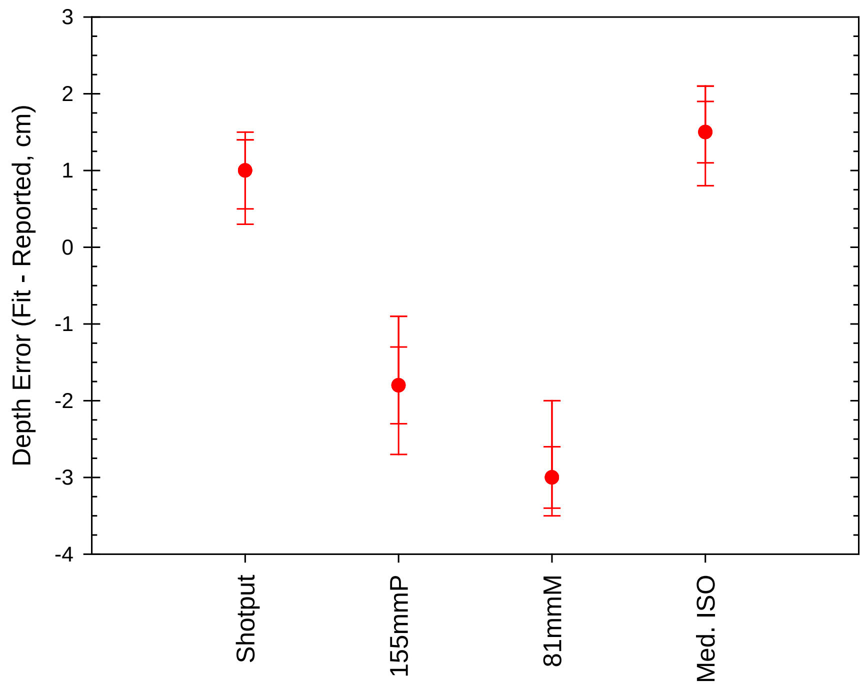

Figure 5-10 –Depth Error Statistics for all Items Emplaced in the IVS.

5.4.4 Additional Calibration Activities

There was a test pit provided onsite, near the IVS, which was used to further populate our reference library of TOI fit parameters. These data will provide additional training data to the classification demonstrators. Please refer to the ESTCP Live Site Demonstrations Plan for further details.

After a review of our signature libraries, signatures for the 155mm Projectile and 4.2-in Mortar were collected. Measurements were made in the required orientations: vertical - nose up, vertical - nose down, horizontal, and at a 45° incline, nose up. A measurement of the horizontal 155mm Projectile was not made in the pit as the same measurement was readily available from item T-002 in the IVS.

5.5 DATA COLLECTION PROCEDURES

5.5.1 Scale of Demonstration

NRL conducted a cued discrimination survey of 1,001 previously-identified anomalies on the northern 1.2 acres of the 3-acre Man-Portable subarea of the 330-acre CIA at Camp Edwards. The anomalies were selected from litter-mode EM61-MK2 data previously collected, provided by the ESTCP Program Office. The survey was conducted using the NRL TEMTADS MP 2x2 Cart in a modified carry mode, as shown in Figure 5-11 (left). The typical cart mode could not be used due to the surface clearance state of the site, so it was operated with the standard handle

replaced with rope as shown in Figure 5-11 (right). At the request of the Program Office, an additional 300 anomalies were investigated on the eastern edge of the MetalMapper subarea to provide some overlap of data collection systems. This portion had the highest anomaly density of both subareas. As part of the demonstration, plastic pin flags were installed at each anomaly location on the source list prior to data collection. Performance of the system response was monitored on a twice-daily basis using the onsite IVS. The data segment (chip) for each anomaly was analyzed and dipole model fit parameters extracted. These results were provided to the ESTCP Program Office along with the archival data.

Figure 5-11 – NRL TEMTADS MP 2x2 Cart Deployed in Modified Litter Mode (left) Man-Portable Subarea Surface Clearance Conditions

5.5.2 Sample Density

The EMI data spacing for the MP System is fixed at 40 cm in both directions by the array design.

5.5.3 Quality Checks

Preventative maintenance inspections are conducted at least once a day by all team members. Any deficiencies will be addressed according to the severity of the deficiency. Parts, tools, and materials for many maintenance scenarios are available in the system spares inventory which was onsite. Status on any break-downs / failures which would have resulted in long-term delays in operations would have been immediately reported to the ESTCP Program Office.

Four data quality checks were performed on the EMI data. After background subtraction, the data from the 12 transmit/receive pairs were plotted as a function of time. An example plot is shown in Figure 5-12 for a horizontal 3” diameter x 12” long solid steel cylinder at a depth of 45 cm below the sensor array. The plots were visually inspected to verify that there was a well-defined anomaly without extraneous signals or dropouts. The recorded transmitter current for each transmit period was inspected to insure a good transmit cycle. A transmitter misfire typically does not reach the average peak value and would have a non-standard waveform. An example is shown in Figure 5-13, where transmitter Tx2 misfired (see Figure 5-2 for sensor numbering).

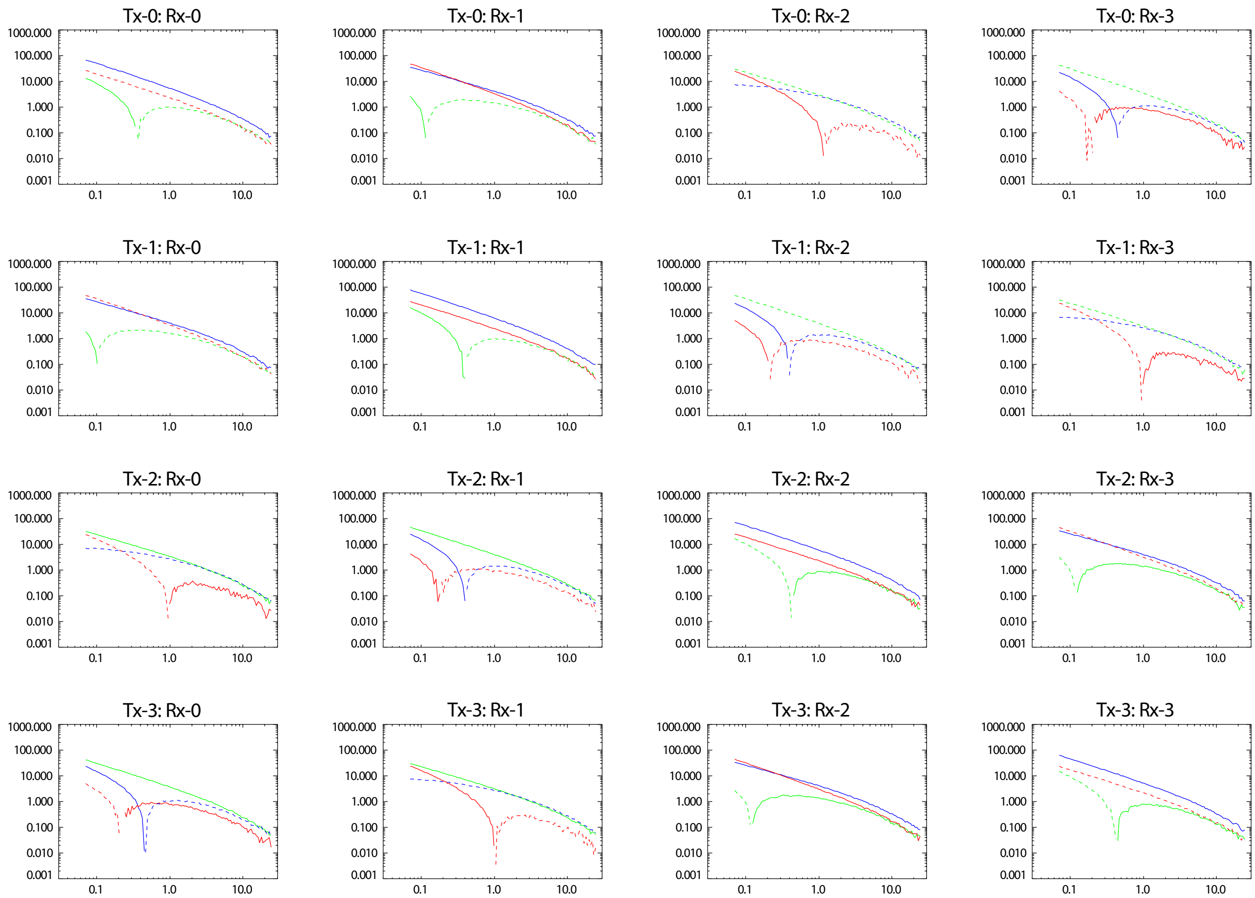

Figure 5-12 – QC Plot for a 3" x 12" solid steel cylinder, horizontal at a depth of 45cm below the sensors. The z,y,x-components in each subplot are shown in blue, green, and red, respectively.

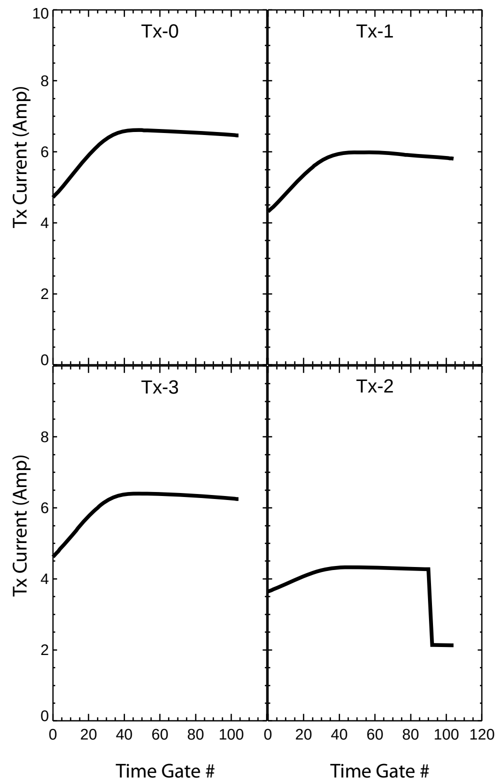

Figure 5-13 – TEMTADS MP 2x2 Cart transmit current waveforms for a bad transmit cycle. In this case, transmitter Tx2 misfired.

Further QC on the transmit/receive cross terms were based on the dipole inversion results. Our experience has been that data glitches show up as reduced dipole fit coherence. Finally, the inversion results are inspected for physical reasonableness and that the fitted location of the anomaly is within the 40cm footprint of the sensor array.

Any data set which has been deemed unsatisfactory by the data analyst is flagged and not processed further. The anomaly corresponding to the flagged data will be logged for future re-acquisition. Data which meet these standards are of the quality typical of a TEMTADS system.

5.5.4 Data Handling

Data were stored electronically as collected on the backpack data acquisition computer hard drive. Approximately every two survey hours, the collected data were copied onto removable media and transferred to the data analyst for QC/analysis. The data were moved onto the data analyst's computer and the media is recycled. Raw data and analysis results were backed up from the data analyst's computer to external hard disks daily. These results were archived on an internal file server at NRL or SAIC at the end of the survey. Examples of the TEMTADS file formats are provided in Appendix C. All field notes / activity logs were written in ink and stored

in archival laboratory notebooks. These notebooks are archived at NRL or SAIC. Relevant sections are reproduced in reports such as this document. Dr. Tom Bell is the POC for obtaining data and other information. His contact information is provided in Appendix B of this report.

5.6 VALIDATION

At the conclusion of data collection activities, all anomalies on the master anomaly list assembled by the Program Office will be excavated. Each item encountered will be identified, photographed, its depth measured, its location determined using cm-level GPS, and the item removed if possible. This ground truth information, once released, will be used to validate the objectives listed in Section 3.0

6.0 DATA ANALYSIS PLAN

6.1 PREPROCESSING

The MP system has four sensor elements, each comprised of a transmitter coil and a tri-axial receiver cube. For each transmit pulse, the responses at all of the receivers are recorded. This results in 48 possible transmitter / receiver combinations in the data set (4 transmitters x 4 receiver cubes x 3 receiver axes). Although the data acquisition system records the decay signal over 122 logarithmically-spaced time gates, the measured responses over the first 17 gates included distortions due to transmitter ringing and related artifacts and are discarded. We further subtract 0.028 ms from the nominal gate times to account for time delay due to effects of the receive coil and electronics [14]. The delay was determined empirically by comparing measured responses for test spheres with theory. This leaves 105 gates spaced logarithmically between 0.089 ms and 25.35 ms. In preprocessing, the recorded signals are normalized by the peak transmitter current to account for any variation in the transmitter output. On average, the peak transmitter current is approximately 7.5 Amps.

The background response is subtracted from each target measurement using data collected at a nearby target-free background location. The background measurements are reviewed for variability and to identify outliers, which may correspond to measurements over targets. In previous testing at our Blossom Point test field and during other demonstrations, significant background variability was not observed. It has been possible to use blank ground measurements from 100 meters away for background subtraction. Changes in moisture content and outside temperature have been shown to cause variation in the backgrounds, necessitating care when collecting data after weather events such as rain.

6.2 PARAMETER ESTIMATION

The raw signature data from the TEMTADS MP 2x2 Cart reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects we invert the signature data to estimate principal axis magnetic polarizabilities for the targets. The

TEMTADS data are inverted using the standard induced dipole response model wherein the effect of eddy currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location [15]. The measured signal is a linear function of the induced dipole moment **m**, which can be expressed in terms of a time dependent polarizability tensor **B** as

$$\mathbf{m} = \mathbf{U}\mathbf{B}\mathbf{U}^{T} \cdot \mathbf{H}_0$$

where **U** is the transformation matrix between the physical coordinate directions and the principal axes of the target and $\mathbf{H}_0$ is the primary field strength at the target. The eigenvalues $\beta_i(t)$ of the polarizability tensor are the principal axis polarizabilities.

Given a set of measurements of the target response with varying geometries or "look angles" at the target, the data can be inverted to determine the local (X,Y,Z) location of the target, the orientation of its principal axes (ϕ,θ,ψ), and the principal axis polarizabilities (β_1,β_2,β_3). The basic idea is to search out the set of nine parameters ($X,Y,Z,\phi,\theta,\psi,\beta_1,\beta_2,\beta_3$) that minimizes the difference between the measured responses and those calculated using the dipole response model. Since the system currently does not know or record the location or orientation of the cart, target location and orientation are known well locally but not well georeferenced.

For TEMTADS data, inversion is accomplished by a two-stage method. In the first stage, the target's (X,Y,Z) dipole location beneath is solved for non-linearly. At each iteration within this inversion, the nine element polarizability tensor (**B**) is solved linearly. We require that this tensor be symmetric; therefore, only six elements are unique. Initial guesses for X and Y are determined by a signal-weighted mean. The routine normally loops over a number of initial guesses in Z, keeping the result giving the best fit as measured by the chi-squared value. The non-linear inversion is done simultaneously over all time gates, such that the dipole (X,Y,Z) location applies to all decay times. At each time gate, the eigenvalues and angles are extracted from the polarizability tensor.

In the second stage, six parameters are used: the three spatial parameters (X,Y,Z) and three angles representing the yaw, pitch, and roll of the target (Euler angles ϕ,θ,ψ). Here the eigenvalues of the polarizability tensor are solved for linearly within the 6-parameter non-linear inversion. In this second stage both the target location and its orientation are required to remain constant over all time gates. The value of the best fit X,Y,Z from the first stage, and the median value of the first-stage angles are used as an initial guess for this stage. Additional loops over depth and angles are included to better ensure finding the global minimum.

Figure 6-1 shows an example of the principal axis polarizabilities determined from TEMTADS array data. The target, a mortar fragment, is a slightly bent plate about ½ cm thick, 25 cm long, and 15 cm wide. The red curve is the polarizability when the primary field is normal to the surface of the plate, while the green and blue curves correspond to cases where the primary field is aligned along each of the edges.

Not every target on the target list will have a strong enough TEM response to support extraction of target polarizabilities. All of the data will be run through the inversion routines, and the results will be manually screened to identify those targets that cannot be reliably parameterized. Several criteria will be used in this process: signal strength relative to background, dipole fit error (difference between data and model fit to data), and the visual appearance of the polarizability curves.

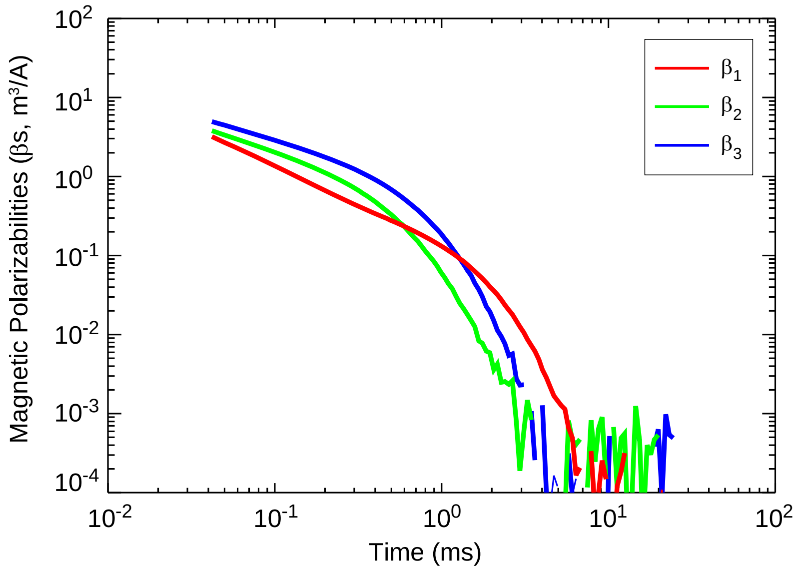

Figure 6-1 – Principal axis polarizabilities for a 0.5 cm thick by 25cm long by 15cm wide mortar fragment.

6.3 DATA PRODUCT SPECIFICATIONS

See Appendix C for the detailed data product specifications.

7.0 PERFORMANCE RESULTS

The performance objectives for the demonstration were summarized in Table 3-1 and are repeated here in Table 7-1. The results for each criterion are subsequently discussed in the following sections.

Table 7-1 – Performance Results for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria	Success? (Yes/No)
Quantitative Performance Objectives				
Instrument Verification Strip (IVS) Results	System responds consistently to emplaced items	Daily IVS data	≤ 10% RMS variation in β amplitudes and fit depth	Yes
Cued Interrogation of Anomalies	Instrument position	Cued data	The center of the instrument was positioned within 40 cm of actual target location for 100% of the anomalies	Yes

7.1 OBJECTIVE: INSTRUMENT VERIFICATION STRIP (IVS) RESULTS

This objective demonstrates that the sensor system was in good working order and collecting physically valid data each day. The Instrument Verification Strip was surveyed twice daily. The amplitude of the derived response coefficients and the fit depth for each emplaced item were compared to the running average of the demonstration for reproducibility.

7.1.1 Metric

The reproducibility of the measured response of the sensor system to the emplaced items defined this metric.

7.1.2 Data Requirements

The tabulated fit parameters for the data corresponding to each emplaced item in terms of derived response coefficients and depth.

7.1.3 Success Criteria

The objective was considered met if the RMS amplitude variation of the derived response coefficients and for the fit depth was less than 10%.

7.1.4 Results

As discussed in Section 5.4.3, the RMS amplitude variations for the magnetic polarizabilities for cued surveys all fell below the 10% cutoff at 3% or less. The RMS amplitude variations for the fit depths were also under 2%.

7.2 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

To collect EMI data of the highest quality for UXO/clutter classification, the anomaly must be illuminated along its three principle axes. To ensure this, the data collection pattern (in this case the TEMTADS array) must be positioned directly over the center of the anomaly.

7.2.1 Metric

The metric for this objective was the percentage of anomalies where the center of the instrument during data collection was within the acceptable distance of the actual target location.

7.2.2 Data Requirements

As the MP System does not have integrated positioning, performance was determined by the offset of each inverted target location from the center of the sensor system. After any reacquisition cycles directed by the data QC process, the offset distance was required to be less than 40cm.

7.2.3 Success Criteria

The objective was considered met if the center of the instrument was positioned within 40 cm of the anomaly fit location for 100% of the cued anomalies. Exceptions were allowed for anomalies where the indicated fit location was within the perimeter of an obstacle such as a tree.

7.2.4 Results

For the MP System cued measurements, the position is not recorded. As such, the metric of requiring that the inverted location of each anomaly not fall outside the sensor footprint (40 cm from the array center) was used. If a fit location indicated that the anomaly was outside the sensor footprint, a new data set was acquired with a refined position until the criterion was met or the indicated position was determined to be unreachable, such as located under a tree.

8.0 COST ASSESSMENT

8.1 COST MODEL

The cost elements tracked for this demonstration are detailed in Table 8-1. The provided cost elements are based on a model developed for cost estimation for the MP System at Camp Beale in 2011 [6]. The model assumes a two-person field crew and one data analyst. For this site a

third person was required for the in-air background measurements. The data analyst was assumed to be available to assist for the background measurements. While the MP system is not currently commercially available, an estimated daily rental rate is provided for comparison to other technologies. The rental rate is based, in part, on the costs of items purchased in prototype quantities (single units) and would presumably decrease significantly if the items were procured at production quantity levels.

8.2 COST DRIVERS

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of anomalies which can be surveyed per day. Higher productivity in data collection equates to more anomalies investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. The thoughtful use of available automation techniques for individual anomaly analysis with operator QC support can moderate this effect.

8.3 COST BENEFIT

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of non-hazardous items that have to be dug or have to be dug as presumptively-hazardous items directly reduces the cost of a remediation effort. The additional information provided by these sensor systems significantly improved anomaly classification performance over traditional methods. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

Table 8-1 – TEMTADS MP 2x2 Cart Tracked Costs

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/Post Survey Activities	Component costs and integration costs • Spares and repairs	 $3,500
	Cost to pack the array and equipment, mobilize to the site, and return • Personnel required to pack • Packing hours • Personnel to mobilize • Mobilization hours • Transportation costs	$12,450 1 16 3 8 $7,250
	Cost to assemble the system, perform initial calibration tests • Personnel required • Hours required	$780 3 2
Survey Costs	Unit cost per anomaly investigated. This will be calculated as daily survey costs divided by the number of anomalies investigated per day. • Equipment Rental (day) • Daily calibration (hours) • Survey personnel required • Survey hours per day • Daily equipment break-down and storage (hours)	**$7.15 / anom.** $190 0.5 2 8 0.5
Processing Costs		**$10.85 / anom.**
Preprocessing	Time required to perform standard data clean up and to merge the location and geophysical data.	3 min/anomaly
Parameter Estimation	Time required to extract parameters for all anomalies.	2 min/anomaly

9.0 SCHEDULE OF ACTIVITIES

Figure 9-1 gives the overall schedule for the demonstration including deliverables.

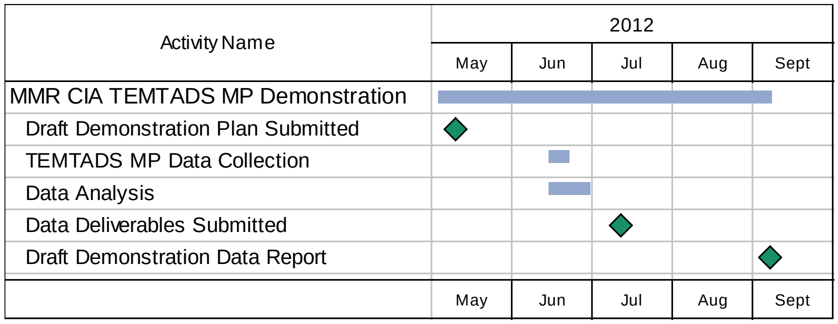

Figure 9-1 – Schedule of all demonstration activities including deliverables.

10.0MANAGEMENT AND STAFFING

The responsibilities for this demonstration are outlined in Figure 10-1. Dan Steinhurst (Nova Research) was the PI of this demonstration. Dan Steinhurst fills the roles of Site / Project Supervisor. Dean Keiswetter (SAIC) and Tamir Klaff (CH2M HILL) served as the SAIC Project Manager and CH2M HILL Project Leads, respectively. Tom Bell (SAIC) served as Quality Assurance Officer. Glenn Harbaugh (Nova Research) was the Site Safety Officer. His duties included data collection and safety oversight for the entire team. Jim Kingdon (SAIC) served as Data Analyst while Andrew Gascho (CH2M HILL) and Matthew Barner (CH2M HILL) trained as Data Analysts. Matthew Barner and Andrew Louder (CH2M HILL) served as Data Acquisition Operators.

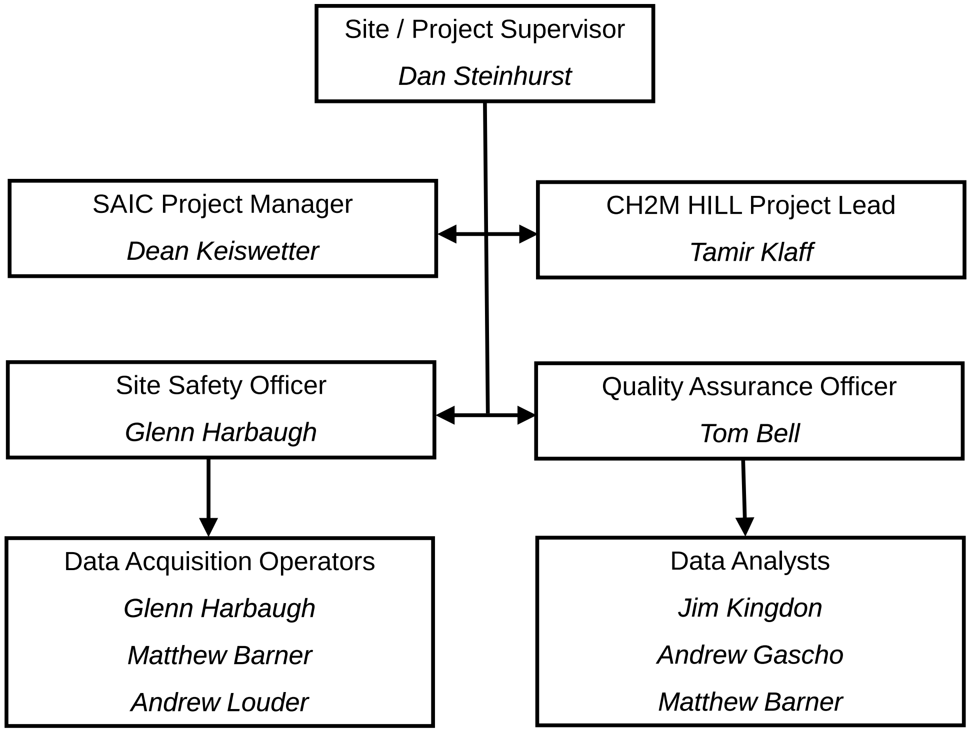

Figure 10-1 – Management and Staffing Wiring Diagram

11.0 REFERENCES

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12. “2010 ESTCP UXO Classification Study, Rougemont, NC, ESTCP MR-1034, Data Demonstration Report, Former Camp Butner, MTADS Discrimination Array (TEMTADS) Survey,” N. Khadr, J.B. Kingdon, G.R. Harbaugh, and D.A. Steinhurst, NRL Memorandum Report NRL/MR/6110—11-9366, Naval Research Laboratory, Washington, DC, October 20, 2011.

13. “2011 ESTCP UXO Live Site Demonstrations, Vallejo, CA, ESTCP MR-1165, Demonstration Data Report, Former Mare Island Naval Shipyard, MTADS Discrimination Array (TEMTADS) Survey,” J.B. Kingdon, T.H. Bell, M.J. Howard, C.E. Blits, G.R. Harbaugh, and D.A. Steinhurst, NRL Memorandum Report NRL/MR/6110—11-9397, Naval Research Laboratory, Washington, DC, April 5, 2012.

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APPENDIX A. HEALTH AND SAFETY PLAN

An abbreviated Health and Safety Plan was generated for this demonstration. All emergency information such as contact numbers and directions to nearby medical facilities are provided in that document. The contents are reproduced here.

A.1 DIRECTIONS TO FALMOUTH HOSPITAL

Directions to the Falmouth Hospital in Falmouth, MA are as follows, starting at the main gate to Camp Edwards on Connery Avenue. See Figure A-1 for the overall route.

1) Head Northeast on Connery Avenue for 1.4 miles.
2) At the traffic circle, take the 3rd exit onto MA-28 South, drive for 9.1 miles.
3) Turn Right onto Ter Huen Drive, drive for 0.1 miles.
4) Turn Left onto Bramble Bush Drive, Falmouth Hospital is on the Right.

Falmouth Hospital is located at 100 Ter Heun Drive, Falmouth, MA 02540, (508) 548-5300. The total distance to travel is 10.6 miles and should take 15 minutes.

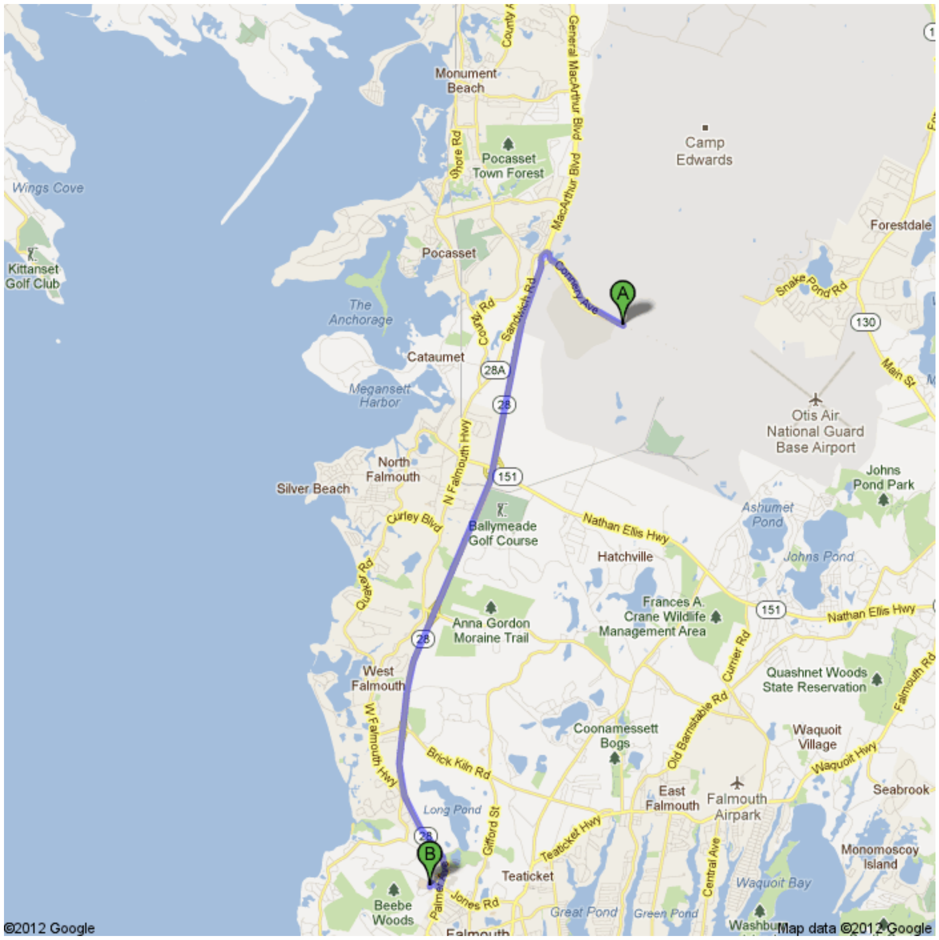

Figure A-1 – Area map showing the location of the Falmouth Hospital with respect to Camp Edwards.

A.2 EMERGENCY TELEPHONE NUMBERS

Telephone numbers for medical fire and other emergencies will be available on site for use by all project personnel in the event of an emergency and are provided in Table A-1. All vehicles will contain a cellular phone (including the phone list) to allow emergency communications in the event of an accident. The telephone area code for this area is 508.

Table A-1 – Emergency Contact Numbers

Agency	Emergency Phone Number	Non-Emergency Phone Number	Location
Bourne Fire Department	911	(508) 759-4412	130 Main Street, Buzzards Bay, MA 02532
Cape Cod Ambulance		(508) 833-3928	15 Jan Sebastian Drive Sandwich, MA 02563
Bourne Police Department	911	(508) 759-4451	175 Main Street, Buzzards Bay, MA 02532
Falmouth Hospital		(508) 548-5300	100 Ter Heun Drive, Falmouth, MA 02540
CVS/pharmacy		(508) 759-1097	6 Head of the Bay Road, Bourne, MA, 02532
Regional Center for Poison Control and Prevention		(800)-222-1222	http://www.maripoisoncenter.com/

APPENDIX B. POINTS OF CONTACT

POINT OF CONTACT	ORGANIZATION	Phone Fax e-mail	Role in Project
Dr. Jeff Marqusee	ESTCP Program Office 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	571-372-6565 (V) 571-372-6386 (F) jeffrey.marqusee@osd.mil	Director, ESTCP
Dr. Anne Andrews	ESTCP Program Office 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	571-372-6565 (V) 571-372-6386 (F) anne.andrews@osd.mil	Deputy Director, ESTCP
Dr. Herb Nelson	ESTCP Program Office 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	571-372-6400 (V) 571-372-6386 (F) 202-215-4844 (C) herbert.nelson@osd.mil	Program Manager, MR
Ms. Katherine Kaye	HydroGeoLogic, Inc. 11107 Sunset Hills Road, Suite 400 Reston, VA 20190	410-884-4447 (V) kkaye@hgl.com	Program Manager Assistant, MR
Mr. Daniel Reudy	HydroGeoLogic, Inc. 11107 Sunset Hills Road, Suite 400 Reston, VA 20190	703-736-4531 (V) druedy@hgl.com	Program Manager's Assistant, MR
Dr. Dan Steinhurst	Nova Research, Inc. 1900 Elkin St., Ste. 230 Alexandria, VA 22308	202-767-3556 (V) 202-404-8119 (F) 703-850-5217 (C) dan.steinhurst@nrl.navy.mil	PI
Mr. Glenn Harbaugh	Nova Research, Inc. 1900 Elkin St., Ste. 230 Alexandria, VA 22308	804-761-5904 (V) glenn.harbaugh.ctr@nrl.navy.mil	Site Safety Officer
Dr. Tom Bell	SAIC 4001 North Fairfax Drive, 4th Floor Arlington, VA 22203	(703)-312-6288 (V) thomas.h.bell@saic.com	Quality Assurance Officer
Dr. Dean Keiswetter	SAIC 120 Quade Drive Cary, NC 27513	(919) 677-1560 (V) dean.a.keiswetter@saic.com	SAIC Project Manager
Mr. Tamir Klaff	CH2M HILL	(202) 596-199 (V) Tamir.klaff@CH2M.com	CH2M HILL Project Lead

APPENDIX C. DATA FORMATS

C.1 TEM DATA FILE (*.TEM)

These data files are a binary format generated by a custom .NET serialization routine. They are converted to an ASCII, comma-delimited format in batches as required. Each file contains 4 data points, corresponding to each transmitter (Tx) cycle. Each data point contains the Tx transient and the corresponding 12 receiver (Rx) transients as a function of time. A pair of header lines is also provided for, one overall file header and one header per data point with the data acquisition parameters. A partial example is provided below.

Line 1 - File Header

```
CPUms,PtNo,LineNo,Delt,BlockT,nRepeats,DtyCyc,nStk,AcqMode,GateWid,Gate
HOff,TxSeq,GateT,TxI_Z,Rx0Z_TxZ,Rx0Y_TxZ,Rx0X_TxZ,Rx1Z_TxZ,Rx1Y_TxZ,Rx1
X_TxZ,Rx2Z_TxZ,Rx2Y_TxZ,Rx2X_TxZ,Rx3Z_TxZ,Rx3Y_TxZ,Rx3X_TxZ,
```

Line 2 - Data Point Header

```
0,1,0,2E-06,0.9,9,0.5,18,2,0.05,5E-05,10,

0            - Start time in ms on CPU clock (always 0)
1            - Data Point Number (always 1)
0            - Line Number (always 0)
2E-06        - Time step for transients (seconds)
0.9          - Base period length (seconds)
9            - Number of Tx cycles in a base period
0.5          - Duty cycle
18           - Number of base periods averaged (or stacked)
2            - Data Acquisition Mode (binned)
0.05         - Gate width as fraction of its own time
5E-05        - Hold-off time (seconds) for first data point
10           - Tx ID number (sensor number + 10)
```

Line 3 - First Data Line in First Data Point

```
,,,,,,,,,,,,2.5E-05,0.454929323587375,-0.000217102604973643,-
9.90293484828453E-05,-9.73085584508137E-
05,0.000226658497598979,2.311827914123E-05,2.17755328848283E-
05,0.000149628473043695,7.99144676070892E-05,-7.19944240815736E-
06,0.000206750834689247,5.7987022583941E-05,2.90883053723187E-05,
```

C.2 ANOMALY PARAMETER OUTPUT FILE

The MTADS Data Analysis System will be used to analyze TEMTADS data. The fitted parameters for each investigated anomaly are distributed as an Excel 2010 spreadsheet, but an excerpt is given in .csv format below for reference purposes. A header line is provided for information followed by a 109-line block for each anomaly. The first line of each block contains the time gate-independent fit parameters and the remaining 108 contain the time gate-dependent parameters for each anomaly.

```
Anomaly_ID,Anomaly_X,Anomaly_Y,Anomaly_Amplitude,Fit_X,Fit_Y,Fit_Depth(
m),Fit_Phi(deg),Fit_Theta(deg),Fit_Psi(deg),Fit_Coherence,Time_Gate,Bet
a1,Beta2,Beta3

28,402751.00,4369521.75,234.34,402750.926,4369521.686,0.151,250.42,2.02
,76.57,0.99612,,,,
,,,,,,,,,,,1,1.47E+00,1.05E+00,1.08E+00
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,,,,,,,,,,,108,2.46E-05,-1.69E-05,-1.60E-04

33,402726.00,4369505.50,15.24,402725.835,4369505.588,0.422,96.25,16.45,
5.26,0.96448,,,,
,,,,,,,,,,,1,1.71E+00,1.23E+00,1.18E+00
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,,,,,,,,,,,108,6.56E-04,-1.91E-03,-1.57E-04
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